ENERGY EFFICIENT WAREHOUSE LIGHTING DESIGN

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INTRODUCTION

Technology available today in the field of lighting controls provides a great opportunity for energy savings in a warehouse. The main electrical load for a warehouse commonly is the lighting system. In this technical paper I will explore the options for energy efficient warehouse lighting that are now available to the lighting designer. The options will be compared in terms of lighting performance, maintenance and life cycle cost. I will show that choosing the proper light source plays a key role in maximizing a warehouse's energy savings. This technical paper will show that using the proper type of fluorescent lighting, together with occupancy sensor control, provides the most energy efficient lighting system for a warehouse.

WAREHOUSE LIGHTING ALTERNATIVES

HIGH INTENSITY DISCHARGE

High intensity discharge (HID) lighting is the most common lighting system used in warehouses. The lamp used in the fixtures is typically either metal halide (MH) or high pressure sodium (HPS), mounted in a hibay or lowbay type light fixture. Mercury vapor lamps are generally not used by the Corps of Engineers due to their inferior performance and will not be discussed further as an option. The light fixtures are all turned on together at the start of the day and will burn continuously throughout the day, consuming considerable energy.

HIGH INTENSITY DISCHARGE WITH HI-LO LIGHT LEVEL CONTROL

This alternative is the same as HID described previously, but in addition occupancy sensors are used to control the light level of selected light fixtures to two levels. Light fixtures along the path of egress and other areas requiring full lighting throughout the day are not controlled via occupancy sensors. Light fixtures in selected areas are controlled to two light levels using occupancy sensors. The high (HI) level is equivalent to full

(100%) brightness, and the low (LO) level is equivalent to approximately 33% light output and 50% power consumption. The HI level corresponds to when the space is occupied, and the LO level corresponds to when the space is unoccupied. The occupancy sensors turn the lights off after a preset interval if no motion is detected during that period. This method saves energy over the previous option (HID, no sensors), equivalent to the energy saved when the selected fixtures are at the LO setting. It is not possible to turn these selected fixtures all the way off due to their restrike time after extinguishing (in the event the space is reentered shortly after the HID lamps are fully extinguished, the light fixtures will not turn on for 15 minutes, an unacceptable tradeoff).

HIBAY FLUORESCENT WITH ON-OFF OCCUPANCY SENSOR CONTROL

This alternative utilizes multiple compact fluorescent lamps mounted in a hibay styled light fixture. Sportlite Inc. of Phoenix, AZ was the first manufacturer of fluorescent hibay light fixtures. Today, both Holophane and LA Lighting (Los Angeles, CA) also manufacture hibay fluorescent light fixtures. The small size of these lamps allows their use in such a fixture and provides a similar light distribution to the HID hibays. Industrial strip fluorescent light fixtures can also be used in this alternative, but their lighting performance generally does not match the hibay fluorescent fixtures at fixture mounting heights exceeding 15 feet. Like the HID HI-LO option, occupancy sensors are used to control light fixtures in selected areas, while other fixtures are left on all day to light egress areas and other areas requiring full lighting throughout the day. Since the hibay fluorescent fixtures can be turned completely off via occupancy sensors, they can potentially save more energy than the HID HI-LO system can save.

COMPARISON OF WAREHOUSE LIGHTING ALTERNATIVES

LIGHTING PERFORMANCE

Lamp Efficiency

Lamp efficiency is measured in lumens per watt. HID lamps have always been considered to outperform fluorescent fixtures in this category. Under this heading we will compare fluorescent lighting first with metal halide and second with high pressure sodium lighting.

Fluorescent vs. Metal Halide

See Table 1 for a comparison of metal halide and fluorescent lamps (1 year is equal to 2600 hours of lamp operation at 10 hours per lamp start). This table takes into account the lumen depreciation of the lamps compared. To calculate the lumens per watt of the metal halide lamps, the ballast wattage was factored in. Table 1 illustrates the following:

- 250 Watt metal halide lamps are not competitive with fluorescent lamps in terms of lumens per watt and lamp life. Metal Halide’s initial lumens per watt are lower than fluorescent, and this trend becomes even more exaggerated over the lamp life.

- 400 Watt metal halide lamps are competitive with fluorescent lamps in terms of lumens per watt when they are installed, but after as little as 2 years only the super metal halide is still competitive with the LEAST efficient of the four fluorescent lamps surveyed.

- The Color Rendering Index (CRI) of fluorescent lamps is superior to metal halide lamps.

- The overall lamp life of fluorescent and metal halide lamps is similar.

TABLE 1 - LAMP CHARACTERISTICS

LAMP TYPE	WATTS	INITIAL LUMENS (LUMENS PER WATT - L/W)	LUMENS @ 1 YEAR (L/W)	LUMENS @ 2 YEARS (L/W)	MEAN LUMENS (L/W)	LAMP LIFE (HRS)	CRI
Octron T-8	32	2950 (92)	2750 (86)	2685 (84)	2600 (81)	20000	82
T-5 Compact Fluorescent	55	4800 (87)	4400 (80)	4368 (79)	4368 (79)	12000	82
T-5 Compact Fluorescent	40	3150 (79)	2960 (74)	2900 (72.5)	2800 (70)	20000	82

Phillips PL-T Comp. Fluorescent	32	2400 (75)	2232 (70)	2184 (68)	2200 (69)	10000	82
Standard Metal Halide	250	22000 (73)	18400 (61)	16500 (55)	17000 (57)	10000	70
Standard Metal Halide	400	36000 (79)	30600 (67)	27720 (61)	25000 (55)	20000	70
Standard Metal Halide	1000	110000 (98)	93500 (85)	84700 (77)	88000 (80)	15000	70
Super Metal Halide	250	23000 (77)	19550 (65)	17700 (59)	15000 (50)	10000	65
Super Metal Halide	400	41000 (90)	34850 (77)	31570 (69)	27500 (60)	20000	70
Super Metal Halide	1000	115000 (105)	97750 (89)	88550 (81)	88000 (80)	12000	70

- 1000 Watt metal halide lamps are more efficient than fluorescent lamps in terms of initial lumens per watt, but factoring in their overall lamp life, this difference becomes very slight. The applicability of 1000 watt metal halide to warehouse applications is not real high due to the typical lighting requirements of 10-30 footcandles and the observance of proper uniformity of illumination throughout the space.

In conclusion, the lamp lumen depreciation of the metal halide lamps over their life, plus their lower CRI, makes them noncompetitive with fluorescent lamps in the category of lamp efficiency.

Fluorescent vs. High Pressure Sodium (HPS), and the Scotopic Response

High pressure sodium lamps have a superior lamp life and lumen per watt ratio to fluorescent lamps. The lumen depreciation of HPS is similar to that of fluorescent lamps. However, the poor CRI of HPS lamps will make them unfit for many warehouse applications.

Another factor which must be considered in the use of HPS lamps for interior lighting is the SCOTOPIC response of the human eye. Studies have shown that the human eye reacts differently to various types of lighting.[1] The human eye is made up of cones and rods.[1] The cone photoreceptors, which are responsible for seeing fine detail and for color vision, provide the photopic visual spectral efficiency.[1] Photopic luminance is thought to be the primary attribute of the spectral distribution of the source with regards to visual performance.[1] The rod system is known to contain a different photopigment than the cone system and as a result has a different spectral response referred to as the scotopic response.[1] The rods are what allow us to see the stars at night, when such dim lighting provides a lack of stimulation to the cones, hence the absence of color vision at night.[1] New laboratory evidence has demonstrated that with almost a full field of view and light levels typical of the interior environment luminances (up to 500 cd/sq. meter), the mean steady state size of the pupil is predominantly controlled by the scotopic energy content of the ambient lighting.[1] Hence, the rods play a part in our daytime vision in addition to at night.[1] This is important because pupil size affects visual acuity and depth of field, which are important processes underlying visual performance.[1] Current visual performance models, such as CIE 19/2, the REA model, and the Clear and Berman model, are based solely either on photopic luminance, or on pupils of fixed size and thus do not capture pupil effects due to spectral differences.[1] Laboratory studies have shown that reductions in visual acuity occur with increasing pupil size for the normally sighted under conditions of moderate to low contrast, but not necessarily at high contrast.[1] The basic reason for the improvement is that a smaller pupil reduces the impact of lens aberrations on visual optical quality.[1] In addition, studies have shown that depth of field always increases when pupil size decreases.[1] This situation is similar to a camera lens, where the larger F-stop (smaller lens opening) provides a greater depth of field.[1]

These results suggest that light sources with scotopically richer spectral content need less photopic luminance to enable a given level of visual performance, visual clarity and brightness perception.[1] Figure 1 below compares various light sources in terms of their scotopic lumens/photopic lumens ratio vs. color rendition index for various light sources. This ratio, when multiplied by a lamp’s standard lumen per watt ratio, will provide the “pupil lumens per watt ratio”, which will better gauge how the lamp will perform for the human eye.[1] The scotopic/ photopic ratio for HPS is .4, and for fluorescent is around 1.5.[1] This translates to a pupil lumens per watt ratio of .4x(29000/ 300) = 39 for HPS, and a pupil lumens per watt ratio of 1.5x(2400/32) = 113 for fluorescent. Thus, when considering the overall quality of the light as the eye pupil utilizes it, fluorescent lighting is about 3 times better than HPS for low to medium contrast tasks. Figure 1 also illustrates that fluorescent lighting slightly outperforms metal halide in scotopic/photopic ratio. Thus, fluorescent lighting is the best overall choice in terms of lamp efficiency.

Color Rendering Index

Table 1 lists the color rendering index (CRI) of fluorescent and metal halide lamps. Fluorescent lamps have the clear edge in this category. High pressure sodium has an even poorer CRI than metal halide. Thus, in terms of color, fluorescent lighting is the best choice for warehouse lighting.

Flexibility

The hibay fluorescent fixtures have multiple lamps (as many as eight). The number of lamps controlled via occupancy sensors in the light fixtures is flexible. For maximum energy savings, all the lamps should be occupancy sensor controlled. However, 1 or 2 lamps in a fixture can be left on all day to provide low level lighting throughout the space. In addition, if a space has multi-level illumination requirements, hibay fluorescent fixtures can accommodate this nicely. In an 8-lamp fixture, for example, you can have 2 lamps on all day, 2 more lamps controlled via occupancy sensors, and the final 4 lamps controlled by a light switch in addition to the sensors. Since each fixture will provide some lighting under any condition, the bay lighting will always be even. Also, because of the reflector design, the light distribution from one fixture is symmetrical with 2, 4, 6 or 8 lamps energized.

Stroboscopic Effect

The eye does not respond instantly to a light stimulus nor does the sensation of vision cease immediately when the stimulus is removed.[2] All light sources operated on alternating current exhibit some cyclic variation in light output.[2] In some cases, this “flicker” causes the observer to see multiple images of a moving object.[2] This phenomenon is known as the stroboscopic effect.[2] Generally, the stroboscopic effect is only a problem on mercury or high pressure sodium fixtures.[2]

MAINTENANCE

Lamp Life

Table 1 illustrates that fluorescent lamps and metal halide lamps have a comparable lamp life. However, due to metal halide’s greater lumen depreciation, the metal halide lamps would require more frequent replacement to match the lighting performance of fluorescent lamps. High pressure sodium lamps have been shown to have the longest life of all the lamps compared, so their replacement interval would be the greatest. However, their poor quality of light has shown them to not be a viable option for warehouse lighting.

Another issue affecting lamp life is lamp burning time per start. Obviously, the use of occupancy sensors will greatly reduce the lamp burning time per start, and consequently reduce the lamp life. Since the controlled lamps will be off most of the time in a warehouse, due to the low occupancy rates, this will not pose a disadvantage. The best solution is to set the occupancy sensors at a minimum 20 to 30 minute time delay, that way the lamp life won’t be affected as severely, while still promoting energy savings.

Premature Lamp Burn Out and Dark Spots

It is inevitable that some lamps burn out prior to their rated lamp life. In the example of a MH or HPS light fixture, this would create a dark spot in the space being lit. With the hibay fluorescent fixtures, a single lamp burning out will not create a dark spot, since the fixture has multiple lamps. Thus, with hibay fluorescent fixtures, relamping needs to be done only once every several years, with no warehouse dark spots forcing additional relamping maintenance.

Relamping Time

The relamping time of HID versus hibay fluorescent fixtures must be compared since the two fixture types have a large difference in the quantity of lamps per fixture. Since each fluorescent fixture has multiple lamps, more time will be required to relamp the fixtures at a scheduled relamping interval. However, this is offset somewhat when you consider that metal halide fixtures, while having only 1 lamp, will require more frequent relamping maintenance due to premature burn out and metal halide's severe lamp lumen depreciation. HID lamps also require more care in handling than fluorescent to avoid damage to the bulb, due to HID's high operating pressure. In addition, the compact fluorescent lamps can be replaced with the power on, since the pin and socket configuration prevents any chance of electric shock, and the lamps remain cool when operating. The additional surrounding light will make relamping easier and safer. With the power on, the maintenance person will know right away if the new lamps work. The power must be turned off to relamp HID fixtures per lamp manufacturer's recommendations. Thus, there is no clear advantage to either HID or fluorescent hibay fixtures in relamping time.

Lamp Cost

Lamp cost is the one area where hibay HID fixtures currently have an advantage over hibay fluorescent fixtures. All three of the major lamp manufacturers, G.E., Phillips and Osram-Sylvania, currently produce compact fluorescent lamps of the types used in hibay light fixtures. Since many of the compact fluorescent lamps are relatively new, or are made by few manufacturers, their price is still relatively high. A 250 watt or 400 watt metal halide lamp costs about $12-$15. The types of compact fluorescent lamps used in hibay fluorescent fixtures cost about $4 to $5 each. Due to the quantity of lamps per fixture in hibay fluorescent fixtures (up to 8), their cumulative cost is greater than for a single HID lamp.

The next and final part of this technical paper will compare the fluorescent and metal halide systems in a life cycle cost analysis, where it will be shown that the higher cost of purchasing the fluorescent lamps is more than offset by the energy savings associated with the fluorescent system.

LIFE CYCLE COST ANALYSIS

The best justification for using hibay fluorescent lighting in a warehouse lies in the life cycle cost analysis between the three alternatives previously discussed:

- Metal Halide, with no sensor controls. This alternative offers the lowest initial cost.

- Metal Halide with HI/LO occupancy sensor control. This alternative costs more up front, but will eventually pay for itself versus metal halide with no sensor control.

- Hibay fluorescent with ON/OFF occupancy sensor control. This alternative has the highest initial cost, but will also save the most money over time.

Case Study: Sharpe Army Depot, General Purpose Warehouse

This was an FY 1996 MILCON project which lent itself very well to the use of occupancy sensors. This facility was a 240,000 square foot warehouse made up almost entirely of long narrow aisles whose light fixtures could be switched off when not in use. The facility has a total of 732 hibay fixtures, with 592 of these fixtures (aisles) controlled via occupancy sensors. The occupancy rate of the warehouse aisles is estimated at 15%. The utility energy rate is $.045/kwh (Western Area Power Administration - WAPA). Note that this energy rate is below average, so the savings illustrated in this case study would be even greater if the cost of electricity were higher. The life cycle cost analysis will be based on a 25-year life cycle and a 3% inflation rate, in accordance with NISTIR 85-3273-9.[3] Note that fuel escalation rates have not been considered in this study, for simplicity. Considering fuel escalation rates would only favor the alternative which saves the most life cycle energy, the hibay fluorescent system. I will show that the high bay fluorescent system is the lowest life cycle cost without this extra advantage (the extra advantage is minimal).

The relamping cost has also been factored into this example. The two HID alternatives have the same relamping cost, but the fluorescent hibay alternative is more expensive. The relamping interval for all alternatives was assumed to be 4.5 years. This is roughly equivalent to the lamp life of the compact fluorescent lamps (12000 hours) at 2600 hours of operation per year. It has been assumed that the metal halide lamps will be replaced at this same interval, ahead of their 20000 hour lamp life, due to their lumen depreciation and their survival rate. It should be restated at this time that metal halide and fluorescent lamps generally have comparable lamp lives (see Table 1). In this particular case study, the fluorescent lamp chosen happened to have a lower rated life than the HID lamp it was compared to.

One point that should be discussed is the lamp wattages used in this comparison. The metal halide is 400 watts and the fluorescent is 250 watts. This does not seem like a fair comparison until you consider the lumen depreciation of metal halide. See Table 2 below. This data is based on Osram-Sylvania's published standard metal halide and 55W biax lumen depreciation data. It is true that lamps will vary between manufacturers, but we never know which manufacturer's lamp will be installed on a job, and which manufacturer's lamp will be used in the future for relamping. Thus, the lamp data in table 2 should suffice. There is similar reasoning behind why super metal halide was not used in the comparison. There is no guarantee that the fixtures will be relamped with super metal halide lamps in the future.

Table 2 - Lumen Depreciation of 55 Watt Biax Lamps vs. Standard 400 Watt Metal Halide

	INITIAL LUMENS	LUMENS @ 1 YR	LUMENS @ 2 YRS	LUMENS @ 3 YRS	LUMENS @ 4 YRS	LUMENS @ 4.5 YRS
(5) 55W BIAX LAMPS	24000	22000	21840	21600	21600	21600
STAND. 400W MH	36000	30600	27720	25200	24120	23400

When you factor in the scotopic/photopic ratios of the above two lamps, 1.5 for metal halide and 1.75 for fluorescent (see Figure 1), plus the higher CRI of the fluorescent lamps, the two alternatives appear to give comparable lighting in the third year of the comparison (1.5x25200=37800 lumens; 1.75x21600=37800 lumens).

See Tables 3 and 4. Table 3 summarizes system parameters for the 3 alternatives. Table 4 compares the 3 alternatives in terms of life cycle cost.

Table 3- System Parameters

	Stand. 400 Watt Metal Halide	HI/LO 400 Watt Metal Halide	Hibay Fluor-escent, (5) 55 W Lamps

Cost Of System (includes sensors and sensor power packs)	135420	234240	274500
Per Fixture Watts	455	455	250
System Watts (Fixture Watts x 732)	333060	333060	183000
Operating Hours Per Year	2600	2600	2600
#Fixtures at “Full Load” 15% of Time	N/A	592	592
Annual KWH of 15% “Full Load” Fixtures	N/A	105050	57720
#Fixtures at “Low Setting” 85% of Time	N/A	592	N/A
Annual KWH of “Low Setting” Fixtures	N/A	297643	N/A
#Fixtures at “Full Load” 100% of Time	732	140	140
Annual KWH of 100% “Full Load” Fixtures	865956	165620	91000
Annual Operating KWH of Fixtures	865956	568313	148720
Total Annual Operating Costs (Energy Consumption Only)	$38968	$25574	$6692
Lamp Replacement Cost Per Fixture	$12	$12	$25
Relamping Interval (years)	4.5	4.5	4.5
Life Cycle Relamping Cost Based on 3% Inflation Rate	57789	57789	120393

Table 4 - System Comparisons

	HI/LO vs. Stand.	Hibay Fluor. vs. Stand.	Hibay Fluor. vs. HI/LO
System Cost Difference	98820	139080	40260
Annual Energy Savings - KWH	297643	717236	419593
Annual Energy Savings - $	13394	32276	18882
Return on Investment Based on 3% Inflation Rate	8.5 years	5 years	27 months
System Cost Savings For 25 Years	281426	818127	536701

CONCLUSION

This paper has shown that a hibay fluorescent system has many advantages over an HID hibay system. The main advantages are:

- Superior color rendering index (and scotopic effect, a related attribute).

- Potential for greater energy savings, due to the ability to turn fluorescent lamps completely off with occupancy sensors when not in use (HID's can only be reduced to 50% power).

- Metal halide lamps suffer much greater lumen depreciation over their lives in comparison to fluorescent lamps. Thus, while 400 watt and 1000 watt metal halide's intial lumen per watt ratio may be higher than for fluorescent lamps, over the lamp life this advantage is lost.

The two disadvantages of the fluorescent hibay system are the higher initial cost, and the higher relamping cost. These costs have been shown to be more than offset in energy savings. Additionally, large warehouse projects ($8-$12 million) I have been involved with were cost-estimated and awarded well under the programmed construction amount, meaning the extra up-front cost of the hibay fluorescent system with occupancy sensors could be financially justified from the start. Conversely, small projects with tight construction budgets may have a difficult time affording the extra up-front cost of a hibay fluorescent lighting system.

A warehouse is an ideal facility for a hibay fluorescent lighting system with occupancy sensors. In the case study shown above, the hibay fluorescent lighting system with occupancy sensor control is clearly the least cost alternative for the life cycle of the warehouse described. The hibay fluorescent system saves $818,127 over the standard metal halide system, and saves $536,701 over the HI/LO metal halide system, over the 25 year life cycle of the warehouse.

Advances in fluorescent lighting technology have expanded its use to many applications, and should be considered for more of our lighting designs in the future, such as aircraft hangers, maintenance bays and sports facilities.

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